Fitting the MMAMSB at the LHC

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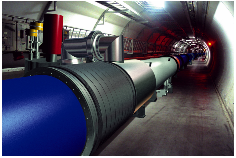
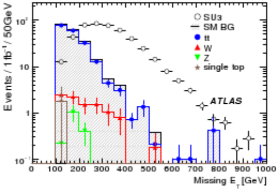
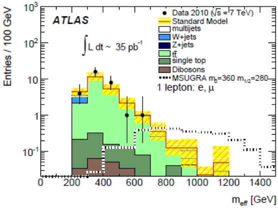
The search for TeV physics is underway.



- LHC has switched on and is running well.



- We are all eagerly awaiting (praying for) any signs of new physics.



- Unfortunately so far we have only seen ....

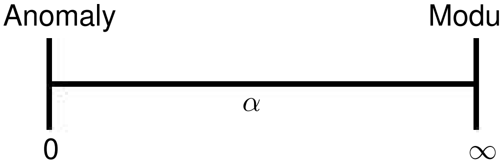
If SUSY is discovered we want to understand the breaking mechanism.

- Many different possibilities for SUSY breaking.
  - CMSSM, gravity (moduli) mediated.
  - mAMSB, anomaly mediated.
  - GMSB, gauge mediated.
  - MMAMSB, mixed moduli anomaly mediated.
- How quickly can we measure the parameters of these models and distinguish between them?

Derived from concrete string compactification of KKLT.

(Kachru, Kallosh, Linde, Trivedi; hep-th/0301240)

- VEVs of the moduli fields are suppressed due to warping.
    - Comparable breaking terms from both gravity and anomaly mediation.
- Phenomenological parameter α interpolates between gravity and anomaly mediation.
    - $\alpha \to 0$, pure anomaly.
    - $\alpha \to \infty$ while $\alpha m_{3/2} = const$, pure moduli.
    - $\alpha = 5$ in original KKLT construction.



MMAMSB phenomenologically

- Soft breaking terms,

$$
\begin{aligned}
M_a &= \frac{m_{3/2}}{16\pi^2}[\alpha + b_a g_a^2], \\
A_{ijk} &= \frac{m_{3/2}}{16\pi^2}[3(n-1)\alpha + (\gamma_i + \gamma_j + \gamma_k)], \\
m_i^2 &= \left(\frac{m_{3/2}}{16\pi^2}\right)^2 [(1-n)\alpha^2 + 4\alpha\xi_i - \dot{\gamma}_i].
\end{aligned}
$$

- $m_{3/2}$ is gravitino mass.
- n are the modular weights of the matter fields.
  - Modulus contributions depend on where the matter fields are located.
  - $n_i = 0, 1, \frac{1}{2}$ for location on D3, D7, intersection.
- Also have tanβ as a free parameter.
- Other terms, $\mathcal{O}(1)$.

(Choi, Falkowski, Nilles, Olechowski, Pokorski; hep-th/0411066)

(Choi, Jeong, Okumura; hep-ph/0504037)

(Falkowski, Lebedev, Mambrini; hep-ph/0507110)

A signature of SUSY breaking are the gaugino masses.

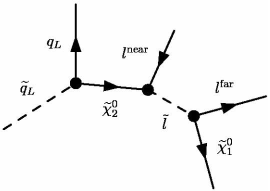
(Choi, Nilles; hep-ph/0702146)

- Gravity, $M_1 : M_2 : M_3 = 1 : 2 : 6$.
  - Also present in many GMSB models (with gauge coupling unification).
  - Gaugino mediation.
  - Large volume compactification (Type IIB string theory).
- Anomaly, $M_1 : M_2 : M_3 = 3.3 : 1 : 9$.
- MMAMSB, $(\alpha + 3.3) : (2\alpha + 1) : (6\alpha - 9)$.
  - Need to choose α large enough to avoid tachyonic sleptons.
  - Solved in mAMSB by ad hoc m_0.

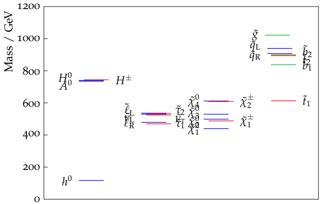
If we can measure these ratios, the breaking scenario should become clear.

Properties of MMAMSB benchmark.

- Chosen to have CMSSM 'like' phenomenology.
    - Two body decay chain.
- Dark matter constraint.
- Masses above previous SUSY limits.
- Satisfy all other constraints.
- α similar to previous constructions.
- $M_1 : M_2 : M_3 = 1 : 1.2 : 2.12$



Parameter	Value
α	4.8
$M_{3/2}$	21×10^3
$\tan\beta$	10
$\text{sign}(\mu)$	+1
n	0.5

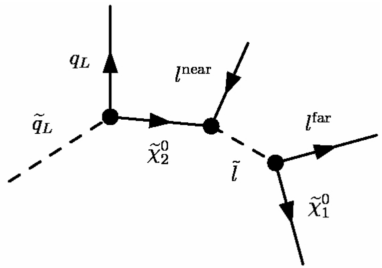


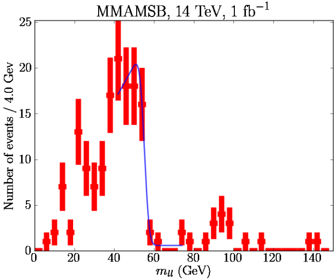
Cascade decay

- Most of the effort at parameter determination has focused on using mass edges.

  (Gjelsten, Miller, Osland; hep-ph/0410303)
- We take invariants between particles in the decay chain.
- For example $m_{\ell\ell}^{\max}$,

$$m_{\ell\ell}^{\max} = \frac{(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{\ell}})(m^2_{\tilde{\ell}} - m^2_{\tilde{\chi}^0_1})}{m^2_{\tilde{\ell}}}.$$



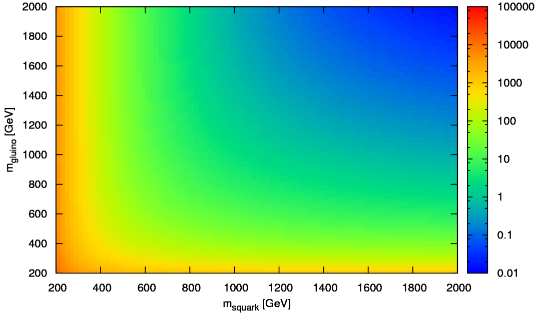


Fit inputs

- Group I, observable in benchmark with 10 fb^{-1} at 7TeV.
  - $m_{\ell\ell}^{\max}$, the dilepton invariant mass edge.
  - $m_{q\ell\ell}^{\max}$, the jet dilepton invariant mass edge.
  - $m_{q\ell}^{\mathrm{low}}$, the jet-lepton low invariant mass edge.
  - $m_{q\ell}^{\mathrm{high}}$, the jet-lepton high invariant mass edge.
- Group II, observable in benchmark with 10 fb^{-1} at 14TeV.
  - $m_{q\ell\ell}^{\mathrm{thr}}$, the jet-dilepton threshold invariant mass edge.
  - $m_{\tilde{q}}^{T2}$, the squark stransverse mass.
  - $m_{\tau\tau}^{\max}$, the di-tau invariant mass edge.
  - m_{tb}^{w}, the weighted top-bottom invariant mass edge.
  - $\Delta m_{\tilde{g}\tilde{\chi}_1^0}$, the mass difference between gluino and LSP.
  - $m_{(\tilde{\chi}_4^0)\ell\ell}^{\max}$, the dilepton invariant mass edge from $\tilde{\chi}_4^0$.
  - $r_{\tilde{\ell}\tilde{\tau}}^{\mathrm{BR}}$, the ratio of selectron (smuon) to stau $\tilde{\chi}_2^0$ decays.

Including event rate information

We can probe the mass scale of SUSY through event rates.



(Dreiner, Krämer, Lindert, O'Leary; arXiv:1003.2648)

- Cross sections vary by orders of magnitude over expected mass range of SUSY.
- Adding rates should improve parameter determination.
- This is a distinguishing feature of this analysis.

Including event rate information

- We use two rate observables to improve our fit.
  - $R_{jj\not{E}_T}$, 2 (or more) jets + missing energy.
  - $R_{jj\ell\ell\not{E}_T}$, 2 (or more) jets + 2 OSSF leptons + missing energy.
- Event rates depend on cross sections, branching ratios and acceptances.
- To get a precise prediction we need to run a Monte-Carlo with full detector simulation.
- Monte Carlo is prohibitively expensive in computing time. (Lester, Parker, White; hep-ph/0508143)
  - A good convergent fit that covers full parameter space needs $\sim 10^6$ points.
  - Can we be more intelligent?

Including event rate information

We use LHC-FASER to include rates.

(Dreiner, Krämer, Lindert, O'Leary; arXiv:1003.2648)

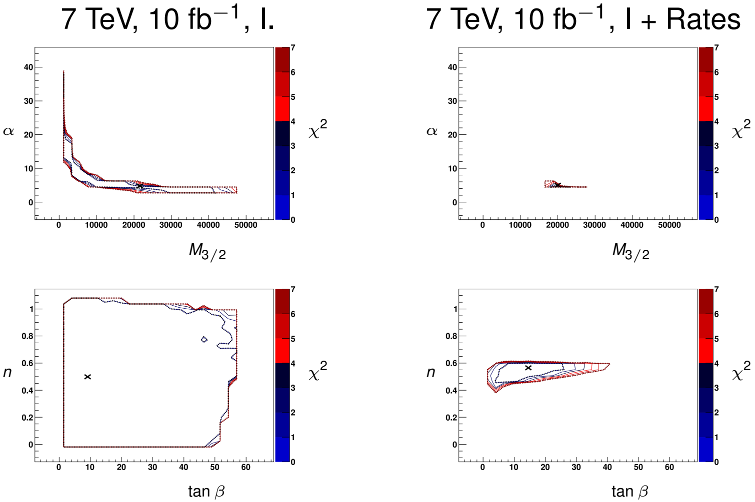
(https://github.com/b4lrog/dev_LHC-FASER)

- Cross-sections smooth so interpolated on grids.
  - NLO for accuracy (Prospino).
    (Beenakker, Hopker, Spira; hep-ph/9611232)
- Branching ratios are calculated via spectrum generator.
- Acceptances calculated via a mix of analytical calculations and generated grids.
- Verified using full Monte Carlo with hadronisation (Herwig++).
  (Bahr et al; arXiv:0803.0883)

Performing the fit

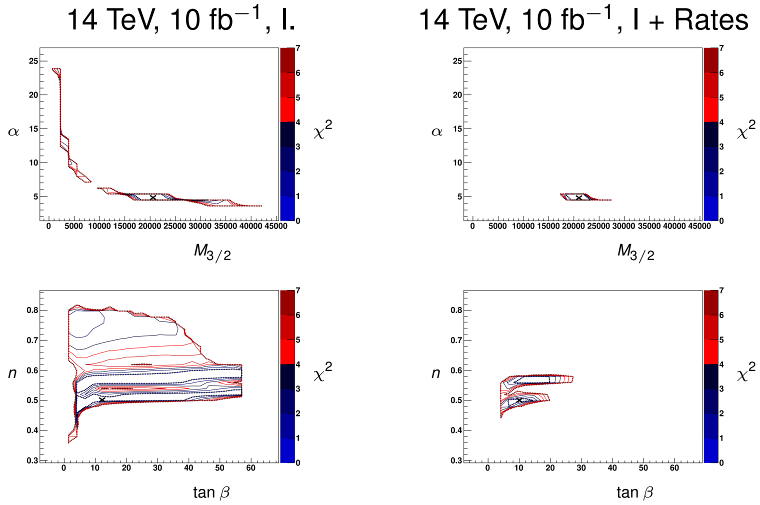
- We adapted Fittino to fit the MMAMSB.
  (Bechtle, Desch, Wienemann; hep-ph/0412012)
  (http://www-flc.desy.de/fittino/)
- Uses Markov Chain Monte Carlo to efficiently scan the parameter space.
- ISASUGRA was used as the spectrum generator.
  (Paige, Protopopescu, Baer; hep-ph/0312045)
  - SPheno used for CMSSM fits.
    (Porod; hep-ph/0301101)
- Fits performed with expected accuracy available with,
  - 10 fb^{-1} at 7 TeV.
  - 1 fb^{-1}, 10 fb^{-1}, 100 fb^{-1} and 300 fb^{-1} at 14 TeV.
- Errors extrapolated from LHC/ILC report.
  (Weiglein et al; hep-ph/0410364)
  - Each observable examined individually
- Fit done to edges to make sure extrapolation is reasonable.

Fitting with 10 fb^{-1} at 7 TeV



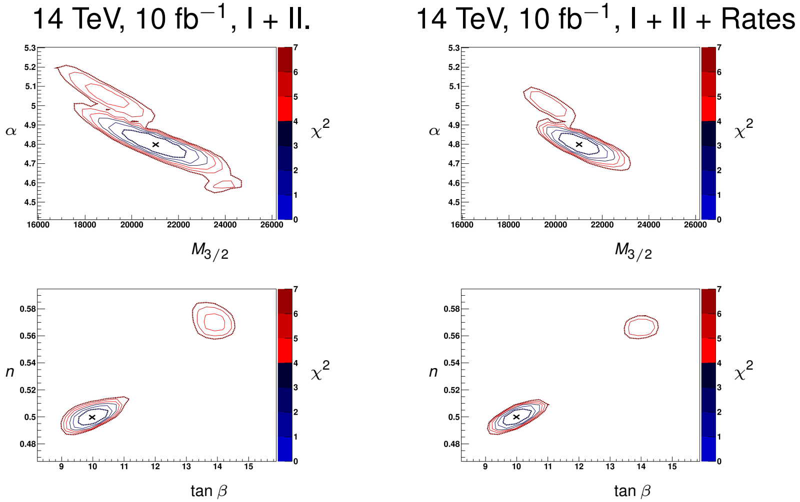
- Rate information constrains parameter space.

Fitting with 10 fb^{-1} at 14 TeV



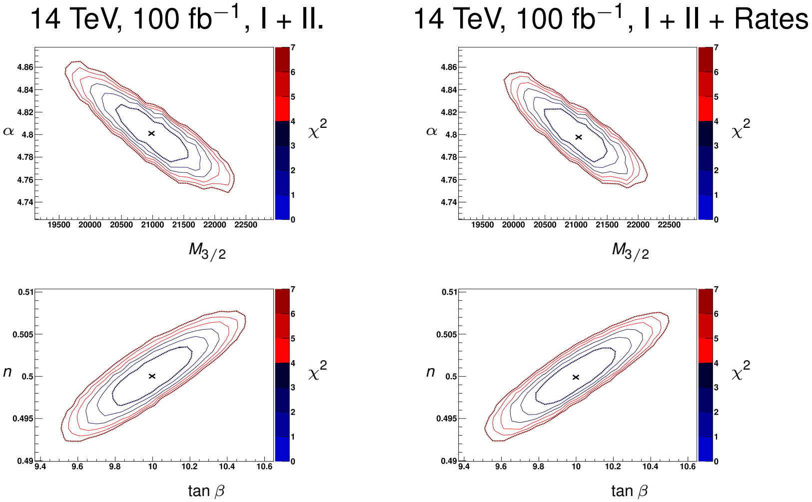
- Even as Group I observables become highly accurate, rate information is required to offer any parameter constraints.

Fitting with 10 fb^{-1} at 14 TeV, Group II observables



- Group II observables significantly constrain parameters.
- Rate information still crucial to determine mass scale.

Fitting with 100 fb^{-1} at 14 TeV, Group II observables

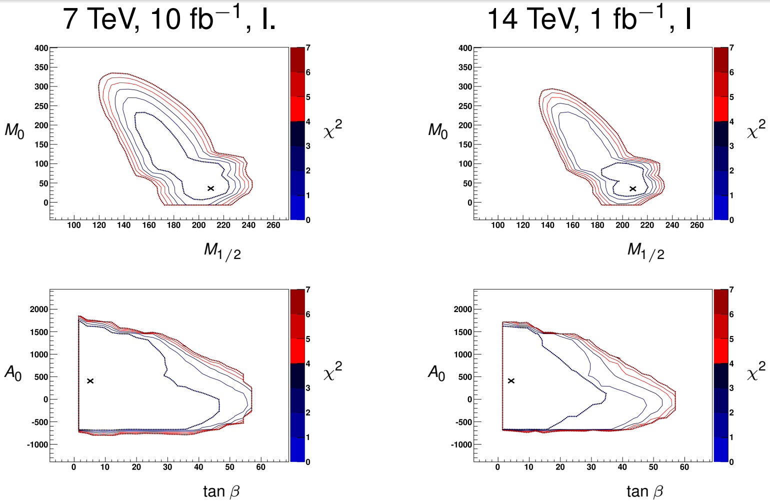


- With 100 fb^{-1}, benchmark point is very accurately fitted.
- All parameters fitted to better than 5%.

We have shown that we can successfully constrain and fit an MMAMSB model.

- Is the CMSSM also able to fit the observables?
- How much data is required to exclude the CMSSM?
- Simultaneously fit, m_0, $m_{1/2}$, A_0, $\tan\beta$.
- Perform fits both with and without rates.

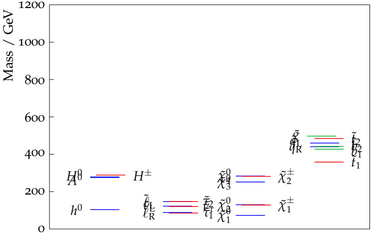
Fitting the CMSSM



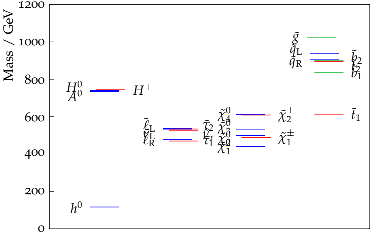
- With early data and Group I observables, CMSSM appears to give a good fit.
- What happens if we include the rate observables?

CMSSM best fit point

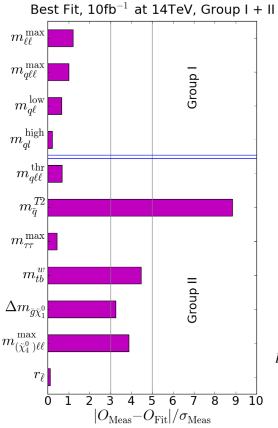
CMSSM best fit, I

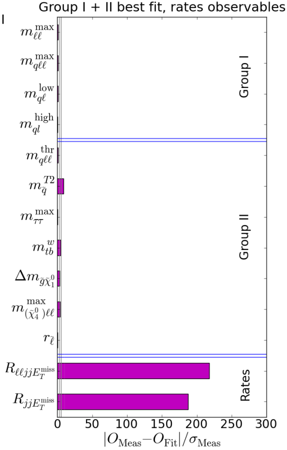


MMAMSB benchmark



- With only Group I edges a very light spectrum is preferred.
- If we include rates, best fit $\chi^2 = 216$.
- 10 fb^{-1} at 7 TeV.
  - $m_{q\ell}^{\text{high}} = 652$ GeV, (benchmark = 312 GeV), 13σ away.
  - $R_{jjE_T^{\text{miss}}} = 231$ fb (benchmark = 113 fb), 5.3σ away.
  - Edges trying to pull spectrum down, rates trying to pull spectrum up.





- With 10 fb^{-1} at 14 TeV we can begin to use the Group II observables.
- Excluded due to $m_{\tilde{q}}^{T2}$, 8.9 σ.
- $m_{\tilde{q}}^{T2}$ pulls mass scale up, $\sqrt{m_{\tilde{q}}^2 - 2m_{\tilde{\chi}_1^0}^2}$.
- Edges pull mass scale down.

- $R_{jj\not{E}_T}$ is 218 σ away.
- Exclusion is stronger with rates with just 10 fb^{-1} at 7 TeV.

Conclusion and future work

- The MMAMSB is a model that contains both moduli and anomaly SUSY breaking.
- The MMAMSB can be successfully probed at the LHC.
- The MMAMSB can be fitted accurately with early LHC data as long as rate information is used.
- The model can be easily distinguished from the CMSSM and mAMSB.
- mAMSB can also be easily distinguished.
- What can we say about more general models?

Backup Slides

Observable errors

Observable	Nominal Value	Uncertainty 10fb^{-1} @7TeV	1fb^{-1} @14TeV	10fb^{-1} @14TeV	100fb^{-1} @14TeV	300fb^{-1} @14TeV	LES	JES
Group I								
$m_{\ell\ell}^{\max}$	55.45	6.01	4.25	1.34	0.43	0.25	0.05	-
$m_{q\ell\ell}^{\max}$	373.4	70.2	49.6	15.7	4.96	2.87	-	3.7
$m_{q\ell}^{\text{low}}$	223.3	38.0	26.8	8.5	4.40	2.46	-	2.2
$m_{q\ell}^{\text{high}}$	311.9	26.0	18.4	5.8	4.70	4.00	-	3.1
Group II								
$m_{q\ell\ell}^{\text{thr}}$	145.5	-	-	29.6	9.37	5.41	-	1.5
$m_{\tilde{q}}^{T2}$	662.0	-	-	28.2	8.91	5.14	-	7.0
$m_{\tau\tau}^{\max}$	58.94	-	-	15.9	5.04	2.91	-	0.6
m_{tb}^{w}	494.1	-	-	43.0	13.6	7.85	-	4.9
$\Delta m_{\tilde{g}\tilde{\chi}_1^0}$	582.0	-	-	48.5	15.3	8.84	-	5.8
$m_{(\tilde{\chi}_4^0)\ell\ell}^{\max}$	168.6	-	-	9.96	3.15	1.81	0.17	-
$r_{\tilde{\ell}\tilde{\tau}}^{\text{BR}}$	0.457	-	-	0.0114	0.0036	0.0021	-	-

Table: LHC observbles for the MMAMSB benchmark point. The masses and branching ratios have been calculated with `ISASUGRA`. The uncertainty estimates on the observables are based on and have been rescaled as described in the main text. All dimensionful quantities are given in GeV.

Observable	7TeV Value	7TeV Uncertainty	14TeV Value	14TeV Uncertainty
$R_{jj\not{E}_T}$	113	23	2780	556
$R_{\ell\ell jj\not{E}_T}$	11.8	3.5	245	49

Table: LHC event rates for the MMAMSB benchmark point. The event rate includes the NLO production cross section, the branching ratios of the decays and the expected particle acceptances. The event rate includes the NLO squark and gluino production cross section calculated by `PROSPINO`. The acceptances were tested with full parton shower and hadronisation using `Herwig++`, `Rivet` and the anti-k_t jet finder

MMASB fit results

MMAMSB	α 4.8	$M_{3/2}$ (TeV) 21	$\tan\beta$ 10	n 0.5
7 TeV and 10 fb^{-1}				
I	$4.8^{+33.5}_{-1.4}$	22^{+19}_{-21}	9^{+48}_{-8}	$0.5^{+0.5}_{-0.5}$
I + rates	$4.99^{+0.15}_{-0.42}$	$20.0^{+2.9}_{-1.0}$	15^{+10}_{-10}	$0.56^{+0.02}_{-0.10}$
14 TeV and 1 fb^{-1}				
I	$4.8^{+41.0}_{-0.8}$	22^{+15}_{-21}	9^{+48}_{-7}	$0.5^{+0.5}_{-0.1}$
I + rates	$4.80^{+0.31}_{-0.13}$	$21.0^{+1.5}_{-2.1}$	10^{+9}_{-4}	$0.50^{+0.08}_{-0.02}$
14 TeV and 10 fb^{-1}				
I	$4.8^{+0.5}_{-0.6}$	21^{+10}_{-5}	12^{+44}_{-9}	$0.50^{+0.09}_{-0.05}$
I + rates	$4.80^{+0.26}_{-0.12}$	$21.0^{+1.5}_{-1.9}$	10^{+9}_{-3}	$0.50^{+0.07}_{-0.01}$
I + II	$4.80^{+0.07}_{-0.05}$	$21.0^{+1.2}_{-1.3}$	$10.0^{+0.4}_{-0.3}$	$0.500^{+0.005}_{-0.004}$
I + II + rates	$4.80^{+0.04}_{-0.04}$	$21.0^{+0.7}_{-0.7}$	$10.0^{+0.4}_{-0.3}$	$0.500^{+0.005}_{-0.004}$
14 TeV and 100 fb^{-1}				
I	$4.8^{+0.3}_{-0.4}$	21^{+5}_{-4}	10^{+47}_{-4}	$0.50^{+0.09}_{-0.02}$
I + rates	$4.80^{+0.24}_{-0.12}$	$21.0^{+1.5}_{-1.6}$	10^{+7}_{-3}	$0.500^{+0.069}_{-0.008}$
I + II	$4.801^{+0.024}_{-0.023}$	$21.0^{+0.5}_{-0.5}$	$9.99^{+0.19}_{-0.19}$	$0.500^{+0.003}_{-0.003}$
I + II + rates	$4.798^{+0.023}_{-0.019}$	$21.0^{+0.4}_{-0.5}$	$10.00^{+0.19}_{-0.19}$	$0.500^{+0.003}_{-0.003}$

Table: Fits to MMAMSB parameters for our chosen benchmark point. Fits are done with various sets of observable groups (I and II) and errors. Fits are also done with and without the rates observables.

CMSSM fit results

CMSSM	M_0 (GeV)	$M_{1/2}$ (GeV)	$\tan\beta$	A_0 (GeV)	χ^2	χ^2/d.o.f
7 TeV and 10 fb^{-1}						
I	36^{+189}_{-21}	210^{+12}_{-58}	5^{+40}_{-3}	405^{+1256}_{-1056}	0.12	0.12
I + rates	78	413	7.8	649	216	72.0
14 TeV and 1 fb^{-1}						
I	35^{+59}_{-12}	208^{+10}_{-21}	$4^{+29}_{-1.0}$	409^{+1237}_{-1038}	0.23	0.23
I + rates	69	379	7.6	580	334	111
14 TeV and 10 fb^{-1}						
I	$35.3^{+47.8}_{-4.8}$	$208.4^{+3.2}_{-10.1}$	5^{+27}_{-2}	373^{+801}_{-742}	2.1	2.1
I + rates	59	331	9.4	538	1643	548
I + II	39	210	8.0	364	122	15.3
I + II + rates	57	328	6.5	531	1806	180
14 TeV and 100 fb^{-1}						
I	$33.6^{+2.5}_{-2.1}$	$207.3^{+2.1}_{-2.4}$	$4.7^{+2.2}_{-1.2}$	365^{+112}_{-105}	11.8	11.8
I + rates	51	319	8.0	542	2533	844
I + II	38	203	8.1	354	907	113
I + II + rates	173	311	5.8	502	4043	404

Table: Best fit points for CMSSM and minimum χ^2 for that point and associated set of observables. We only include the 1σ environment when the best fit point is not excluded at the 99.9% confidence level. We see that rates is extremely effective at ruling out CMSSM.